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High-Precision and High-Efficiency Micromachining of Chemically Strengthened Glass Using Ultrasonic Vibration

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Abstract

This paper addresses axial ultrasonic-vibration-assisted helical milling of chemically strengthened glass. Axial ultrasonic vibration was applied to a milling tool using an ultrasonic device to obtain longer tool life, higher machining accuracies, and improved cutting efficiency. The effects of ultrasonic vibration on microscale, through-hole helical milling of chemically strengthened glass were investigated and the impact of three cutting parameters (feed velocity, pitch per revolution, rotation speed) on the characteristics of surface chippings was evaluated. The results of the cutting tests clearly showed a reduction of chipping size and an improvement in tool life by using the proposed manufacturing method. Finally, optimum cutting conditions were proposed based on the results of the milling tests.

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Keywords: Helical milling; Micromachining; Glass; Ultrasonic vibration

1. Introduction

Recently, chemically strengthened glass has been used for mobile display device touch screens such as smartphones and tablet PCs. The advantage of chemically strengthened glass is its high strength and stiffness; it is approximately five times stronger than soda-lime glass [1]. The demands for micro through-hole drilling of chemically strengthened glass are increasing because of the miniaturization of mechanical components. However, in micro drilling of chemically strengthened glass, significant machining accuracy and efficiency have not been realized, because the high hardness and brittleness cause rapid tool wear and chipping at the inlet and outlet of machined holes. In addition to the problems regarding the machined surface, decreased tool life caused by low tool rigidity and the high hardness of chemically strengthened glass, must be considered.

There are several methods to machine accurate, small diameter holes, such as laser machining, electric discharge machining (EDM), and electron beams. However, it is difficult to cut cleanly and efficiently using a laser. The production costs for laser machining, EDM, or electron beam machining are relatively expensive, and the quality of the machined holes tends to be low [2]. Considering these facts, mechanical machining methods using a solid tool are more suitable for glass drilling. However, the conventional drilling of chemically strengthened glass produces high cutting forces and leads to low quality machined surfaces and rapid tool wear.

To machine difficult-to-cut materials, the authors propose using ultrasonic-vibration-assisted machining as an effective method, which could improve the cutting forces, tool wear, chip generation, surface quality, and so on [3]. Several authors [4, 5] have proven that ultrasonic-vibration-assisted machining is an efficient cutting method for improving the machinability of several materials such as aluminum, Inconel, and composite materials.

In this study, an ultrasonic-vibration-assisted helical milling method was proposed. The effects of ultrasonic vibration on the micro through-hole helical milling of

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chemically strengthened glass were investigated. Specifically of interest were the chipping size of machined holes, thrust forces, and tool life. Further, the effect of three cutting parameters, including feed rate, pitch per revolution, and rotation speed, on surface chipping was evaluated. Finally, optimum cutting conditions were proposed based on the results of cutting tests.

2. Principles of ultrasonic-vibration-assisted helical milling

2.1. Axial ultrasonic-vibration-assisted micromachining

In this study, axial ultrasonic vibration was applied to a micro tool using a specially designed spindle and an ultrasonic device. Conventional drilling uses constant feed rates, and therefore, the contact between the tool and the workpiece is continuous. Consequently, cutting fluid is not efficiently supplied at the cutting point and chip evacuation is further hampered. On the other hand, when axial ultrasonic vibration is applied to the tool, the intermittent cutting mechanism realizes smooth drilling, improved flow of the cutting fluid, and better chip evacuation.

In addition, the workpiece is fractured by the tool tip during the intermittent cutting process with large acceleration forces. Neugebauer et al. [6] mentioned that, in particular, hard and brittle materials such as glass and ceramics can be properly machined with ultrasonic-vibration-assisted techniques because the fracturing effect results in reduced cutting forces.

2.2. Kinematics of helical milling

The major differences between drilling and helical milling processes result from the kinematic conditions [7]. In the drilling process, the diameter of the machined hole is same as the tool diameter. In the helical milling process, the diameter of the machined hole is determined by the tool diameter in combination with the radius of the helical path (Fig. 1).

The helical milling process can be positionally defined by simultaneous movement along a helical path (*X*- and *Y*-directions) with an axial feed (*Z*) at a defined pitch. In comparison to conventional drilling, the helical milling process often reduces thrust forces and surface chipping, and provides better chip evacuation.

There are three, variable, and key factors in helical milling, including feed rate, pitch per revolution, and rotation speed. In this research, the effects of these three cutting parameters relative to surface chipping were investigated.

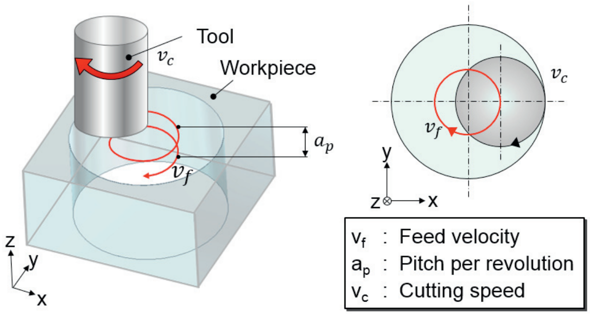

Fig. 1. Kinematics of helical milling.

3. Experimental setup and procedure

A three-axis vertical machining center (V33, Makino Milling Machine Co., Ltd.) with a maximum rotation speed of 8000 min^{-1} was used for the cutting tests. Figure 2 and 3 show the experimental setup; chemically strengthened glass was fixed to the jig using solid wax. A three-component, piezoelectric dynamometer (9257B, KISTLER Co., Ltd.) was set up between the workpiece and the machine tool table to measure the cutting force.

A specially designed ultrasonic vibration spindle was controlled by an ultrasonic vibration controller (Sonic Impulse SD-100, Taga Electric Co., Ltd.) which was used to supply the axial ultrasonic vibrations to the tool. The frequency and amplitude were 70 kHz and 4.0 μm, respectively. Electroplated diamond tools (0.4 mm in diameter) were used in this study (Fig. 4). These tools were fabricated by using diamond grains, which were applied as a single layer onto the metal core with electroplating. The thickness of the chemically strengthened glass was 1.1 mm.

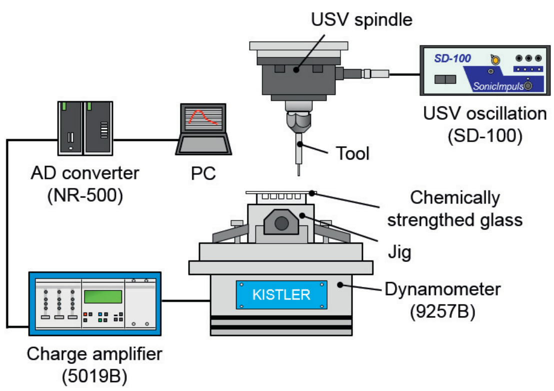

Fig. 2. Experimental setup. (USV, ultrasonic vibration)

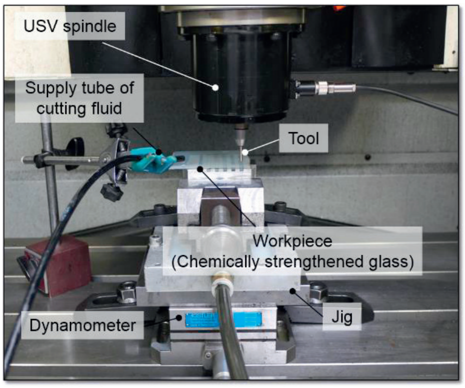

Fig. 3. Actual experimental setup.

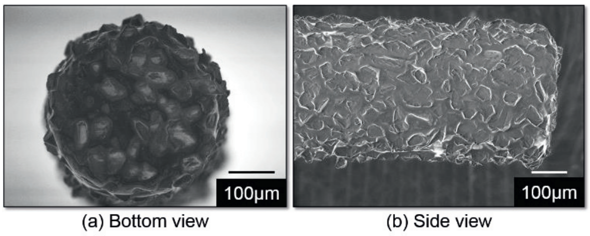

Fig. 4. Scanning electron microscopy image of electroplated diamond tool.

4. Effects of ultrasonic vibration on helical milling

Two types of cutting experiments were performed and compared: conventional helical milling and axial ultrasonic-vibration-assisted helical milling. The chipping sizes at the inlet and outlet of the machined holes were measured using a digital microscope (VHX-600, KEYENCE Co., Ltd.). As shown in Fig. 5, the chipping size was defined as the maximum chip width in the radial direction. Table 1 shows the cutting conditions for helical milling. The cutting process was performed according to the NC helical milling program.

The results of the chipping size and the average thrust force are shown in Fig. 6 and Fig. 7, respectively. The results clearly show that the chipping size and the thrust force were reduced by applying ultrasonic vibration. In conventional helical milling, high thrust forces induce chippings at machined holes, tool wear, and tool breakage. The cutting force was decreased by applying axial ultrasonic vibration to the tool, and also by the intermittent cutting process with large accelerations over a short period during tool contact with the workpiece.

For each experiment, the maximum number of drilled holes without tool changeover was counted. The cutting tests were performed twice, and the results are summarized in Table 2. The maximum number of drilled holes reached with ultrasonic vibration helical milling was approximately 30 times greater than that of conventional helical milling. This was due to the reduction of the thrust force and tool wear in axial ultrasonic vibration helical milling.

Table 1. Cutting conditions for helical milling.

Condition Type	Condition
Axial USV	70 kHz/4.0 μm
Tool	Electroplated diamond tool (Φ 0.4 mm)
Cutting fluid	Soluble type
Feed velocity	80 mm/min
Pitch per revolution	0.05 mm
Rotation speed	8000 min^{-1}
Hole depth	1.1 mm (penetrated)

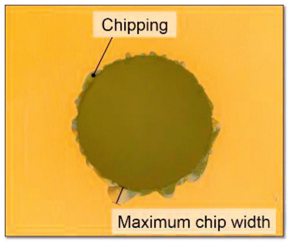

Fig. 5. Digital microscope image of surface chipping.

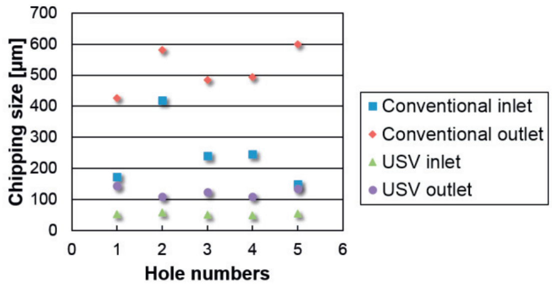

Fig. 6. Comparison of chipping size.

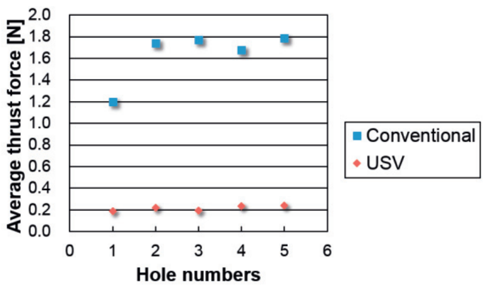

Fig. 7. Comparison of average thrust force.

Table 2. Maximum number of drilled holes.

Type of cut	Maximum number of drilled holes	
	1st	2nd
Conventional helical milling	5	9
USV-assisted helical milling	214	290

5. Effects of cutting parameters on surface chipping

All experiments were performed using the same tools as the former experiment (Fig. 4), with the application of axial ultrasonic vibration. Cutting tests were repeated five times for each condition, and the average values for chipping size were plotted.

5.1. Effects of feed velocity

To investigate the effects of feed velocity of the tool center point on the characteristics of surface chippings, feed velocity was varied from 1 to 100 mm/min, at the same pitch per revolution, 0.05 mm, and the same rotation speed, 8000 min^{-1}.

Figure 8 shows that the chipping size at outlet of the machined holes increased with feed velocity, whereas the chipping size at the inlet of machined holes remained constant, independent of feed velocity. In general, glass is strong under compressive loading, but weak in tension. In this experiment, compressive stress was applied to the inlet, whereas tensile stress was applied to the outlet. Therefore, large chippings at the outlet of machined holes were caused by higher thrust forces owing to the high feed velocity.

With respect to the processing time and the chipping size, feed velocities of 80 and 10 mm/min are the optimum values at the inlet and outlet of the milled holes, respectively.

5.2. Effects of pitch per revolution

Figure 9 shows the relationship between chipping size and pitch per revolution, with a feed velocity of 40 mm/min, and rotation speed of 8000 min^{-1}. Figure 9 shows that the chipping size at the inlet of the machined holes increased with increasing pitch size per revolution. The chipping sizes at the outlet of the holes were larger regardless of the increase in the pitch size per revolution. However, small pitch per revolution values showed less dispersion at the outlet of the holes and decreased thrust forces.

Based on the experimental results, a 0.01 mm size pitch per revolution is the optimum cutting parameter at the both inlet and outlet of the milled holes.

5.3. Effects of rotation speed

Shown in Fig. 10 is the relationship between chipping size and rotation speed, and although rotation speed has less of an effect on chipping size relative to feed velocity and pitch per revolution, high rotation speeds are effective in reducing the amount of dispersion. The chipping size at the inlet and outlet of the machined holes decreased with rotation speed. Therefore, the rotation speed of 8000 min^{-1} is the optimum condition at both inlet and outlet.

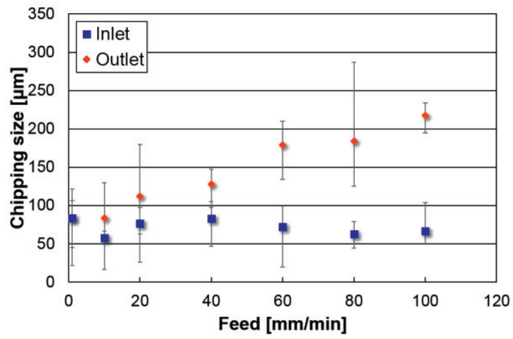

Fig. 8. Effects of feed rate on chipping at inlet and outlet of machined holes.

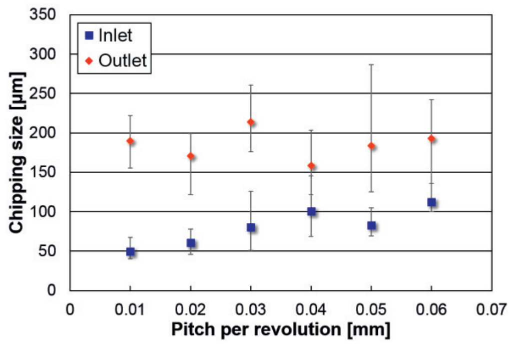

Fig. 9. Effects of pitch per revolution on chipping at inlet and outlet of machined holes.

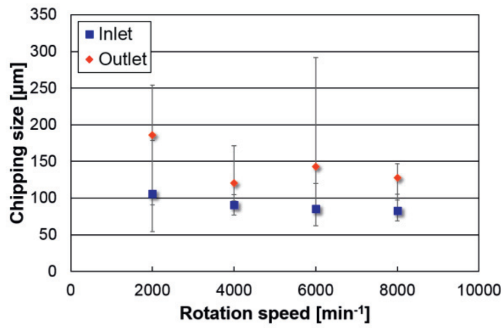

Fig. 10. Effects of rotation speed on chipping at inlet and outlet of machined holes.

6. Experiment under optimum cutting condition

Based on the experimental results in Section 5, optimum cutting conditions were proposed, which are summarized in Table 3. During the processing, the feed velocity and the pitch per revolution were varied based on the depth of the holes (Fig. 11). Near the inlet (①) and outlet (③) of the hole, the axial feed rate was decreased, whereas in the middle of the hole (②) and following penetration (④) the axial feed rate was increased. The rotation speed was fixed at 8000 min^{-1}.

We evaluated the effects of ultrasonic-vibration-assisted helical milling under optimum cutting conditions on the accuracy of machined holes; this is shown in Fig. 12. As shown in Fig. 12, the chipping sizes less than 100 μm were obtained in nearly all 20 holes. Experimental results showed that using optimum cutting conditions, the ultrasonic-vibration-assisted helical milling can drastically reduce the chipping size.

The comparison of chipping size between conventional helical milling and ultrasonic-vibration-assisted helical milling with the optimum cutting conditions is summarized in Table 4. Based on results in Table 4 and Fig. 13, there were large differences in the chipping size between these two milling methods. In particular, by applying the ultrasonic vibration, the average chipping size at the inlet and outlet of machined holes was reduced by 41% and 86%, respectively, relative to conventional helical milling.

Figure 14 shows scanning electron microscope images of the tool bottom and side after machining 20 holes with optimum cutting conditions. While the diamond grains on the tool bottom and side were significantly worn in the conventional helical milling process, the tool used in ultrasonic-vibration-assisted helical milling was in good condition after machining 20 holes, and likely could have continued processing. We expect that the intermittent cutting processes using tool vibration can achieve the low cutting forces and thermal loads required by current micromachining standards. Tool wear can result in serious damage to milled surfaces such as surface chipping; hence, to achieve the desired quality of machined holes and to extend tool life, it is necessary to prevent tool wear.

Table. 3. Optimized cutting condition.

Cutting depth [mm]	Feed rate [mm/min]	Pitch per revolution [mm]	Spindle speed [min^{-1}]
① 0–0.1	80	0.01	8000
② 0.1–1.0	80	0.05	8000
③ 1.0–1.2	10	0.01	8000
④ 1.2–1.6	10	0.05	8000

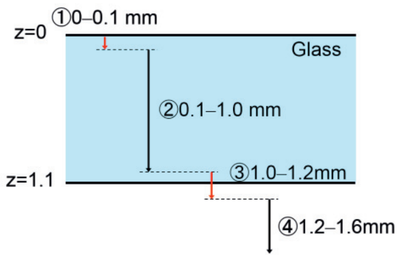

Fig. 11. Schematic view of optimized cutting condition.

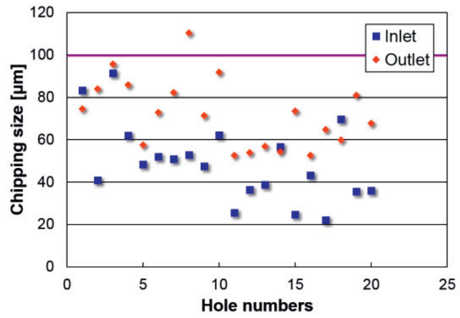

Fig. 12. Chipping size with optimum cutting conditions.

Table. 4. Average chipping size with optimum cutting conditions.

Type of cut	Average chipping size	
	Inlet	Outlet
Conventional helical milling	82.7	509
USV-assisted helical milling	49.0	72.2

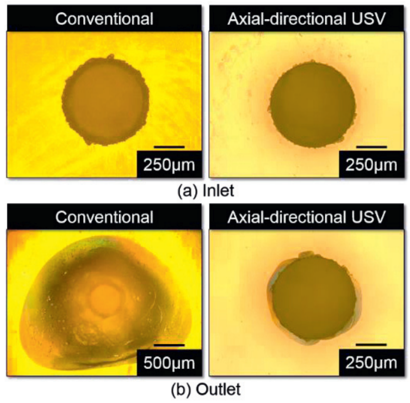

Fig. 13. Digital microscope image of 20th inlet and outlet of machined holes with optimum cutting conditions.

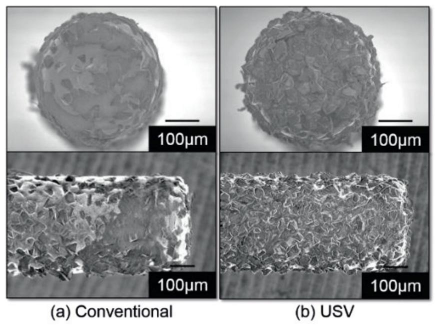

Fig. 14. Scanning electron microscopy image of tool bottom and side after machining 20 holes under optimum cutting conditions.

7. Conclusion

Axial ultrasonic-vibration-assisted helical milling was proposed in this study, and the validity of this method was evaluated. The results showed positive effects, summarized as follows:

1. The chipping size and thrust force decreased when axial ultrasonic vibration was applied to the tool.
2. Ultrasonic-vibration-assisted helical milling reduced tool wear and led to longer tool life.
3. The effect of three cutting parameters (feed rate, pitch per revolution, rotation speed) to the surface chippings was evaluated, and the optimum cutting conditions were proposed based on the experimental results.
4. Under the optimum cutting conditions and using ultrasonic vibration, the average chipping sizes at the inlet and outlet of the machined holes were reduced by 41% and 86%, respectively.

Acknowledgements

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References

[1] R. Gy. Ion exchange for glass strengthening. Materials Science and Engineering B, 149 (2008). p. 159-165.
[2] H. Isobe, Y. Uehara, M. Okada, T. Horiuchi, K. Hara. Visualization of stress distribution on ultrasonic vibration aided drilling process. Journal of Advanced Mechanical Design, Systems, and Manufacturing, 6 (2012). p. 771-780.
[3] C. Nath, M. Rahman. Effect of machining parameters in ultrasonic vibration cutting. International Journal of Machine Tools & Manufacture, 48 (2008). p. 965-974.
[4] D.E. Brehl, T.A. Dow. Review of vibration-assisted machining. Precision Engineering, 32 (2007). p. 153-172.
[5] B. Azarhoushang, J. Akabari. Ultrasonic-assisted drilling of Inconel 738-LC. International Journal of Machine Tools and Manufacturing, 47 (2008). p. 1027-1033.
[6] R. Neugebauer, A. Stoll. Ultrasonic application in drilling. Journal of Materials Processing Technology, 149 (2004). p. 633-639.
[7] B. Denkena, D. Boehnke, J.H. Dege. Helical milling of CFRP-titanium layer compounds. CIRP Journal of Manufacturing Science and Technology, 1 (2008). p. 64-69.